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Details of valence band structure of p-GaAs/AlGaAs symmetric quantum wells unraveled by uniaxial compression

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Abstract. Uniaxial compression has been applied to symmetrically grown quantum wells of GaAs with Be-modulation-doped barriers of AlGaAs. We demonstrate how the analysis of the influence of uniaxial compression on the Shubnikov–de Haas oscillations can unravel details of the valence band structure; e.g. the question of whether or not the ground state is doubly degenerate or is consisting of two slightly different bands. We find the latter to be the case, and that the carrier densities in both of the two bands decrease under the application of the uniaxial compression; however, with different pressure coefficients.

Introduction

The spin-orbit coupling has important influence on the band structure of III–V semiconductors. Especially so, when the valence band is concerned. This applies to bulk materials as well as to heterostructures. For the latter, in the case of a single heterostructure (triangular quantum well) the interface electric field gives rise to a so-called *interface spin-orbit coupling* or *Rashba asymmetry* [1, 2], which causes a splitting of the m_j -degeneracy away from $k = 0$. Contrary to this, in the case of a double heterostructure (rectangular quantum well), there is no electric field in the well-provided it has a flat bottom — and the m_j -degeneracy remains. The problem with this nice picture is the lack of control of the potential shape details in actual samples. The only information which is usually accessible concerns the sequence of layers in the heterostructure samples. Thus, if there is just one interface, say GaAs/AlGaAs, the potential might coarsely be described as ‘triangular’, and — if there are two interfaces AlGaAs/GaAs/AlGaAs — as ‘rectangular’. The first search to see the influence of the two potential types on the splitting of the m_j -degeneracy was made in magnetotransport, e.g.: Shubnikov–de Haas oscillations [3]. The feature looked for was a doubling of the frequency of B^{-1} -oscillations in fields strong enough to split the degeneracy expected for a rectangular well. The result was successful in the sense that a doubling was observed in rectangular wells, but not in triangular ones.

We have previously analysed our measurements of the influence of uniaxial compression on the Shubnikov–de Haas oscillations observed in rectangular quantum wells by looking at the ratio of B^{-1} -frequencies [4, 5]. Our conclusion was — with some reservations — that this influence was modest. By the present communication we want to present a new analysis, in which we give up the focus on the frequency ratio. By this new analysis we demonstrate how uniaxial compression can be used to unravel some finer details of the valence band ground state in rectangular quantum wells. Namely

that, instead of a doubly degenerate band, it has two closely lying bands which behave differently under uniaxial compression.

1 Samples and measurements

The wafer was grown by molecular beam epitaxy on a (100) semiinsulating GaAs substrate. The grown layer sequence was as follows: 0.5 μm GaAs, 0.2 μm $\text{Al}_{0.5}\text{Ga}_{0.5}\text{As}$, 5 nm $\text{Al}_{0.5}\text{Ga}_{0.5}\text{As:Be}(2 \times 10^{18} \text{ cm}^{-3})$, 25 nm $\text{Al}_{0.5}\text{Ga}_{0.5}\text{As}$, 10 nm GaAs, 25 nm $\text{Al}_{0.5}\text{Ga}_{0.5}\text{As}$, 5 nm $\text{Al}_{0.5}\text{Ga}_{0.5}\text{As:Be}(2 \times 10^{18} \text{ cm}^{-3})$, 0.1 μm $\text{Al}_{0.5}\text{Ga}_{0.5}\text{As}$, and 10 nm GaAs:Be($4 \times 10^{18} \text{ cm}^{-3}$), i. e.: A 10 nm GaAs layer is surrounded by layers of $\text{Al}_{0.5}\text{Ga}_{0.5}\text{As}$, which are doped by Be in 5 nm thick layers placed 25 nm away to both sides of the GaAs layer. This fully symmetric layer structure is identical to the one reported on in [4], and deviates slightly from the one in [5] which had one of the Be-doped layers placed 50 nm away from the GaAs layer. At ambient pressure the sample has $3.38 \times 10^{15} \text{ m}^{-2}$ holes as determined from Hall measurements. Details of the experimental technique have been reported in [6]. The ranges of the experimental parameters are: 0–5 T, 0–3.4 kbar compression along (110), 1.45 K.

2 The Shubnikov–de Haas oscillations and the analysis

In Fig. 1 we show the Shubnikov–de Haas oscillations of the square resistance R_{sq} with the reciprocal magnetic field as the horizontal variable, and with the uniaxial compression as parameter. We are obviously not dealing here with a single oscillation

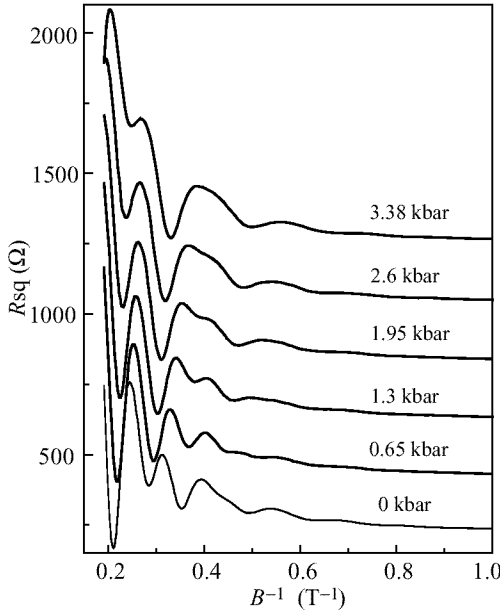


Fig. 1. Shubnikov–de Haas oscillations versus inverse magnetic field with the uniaxial (110) compression as parameter.

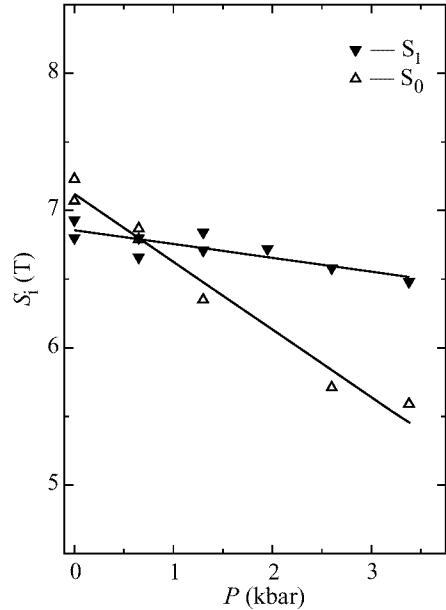


Fig. 2. SdH frequencies for the two bands versus uniaxial (110) compression. The straight lines present least-squares fits: $S_0 = 7.12 - 0.49P$ and $S_1 = 6.86 - 0.10P$, where S is in tesla and P in kbar.

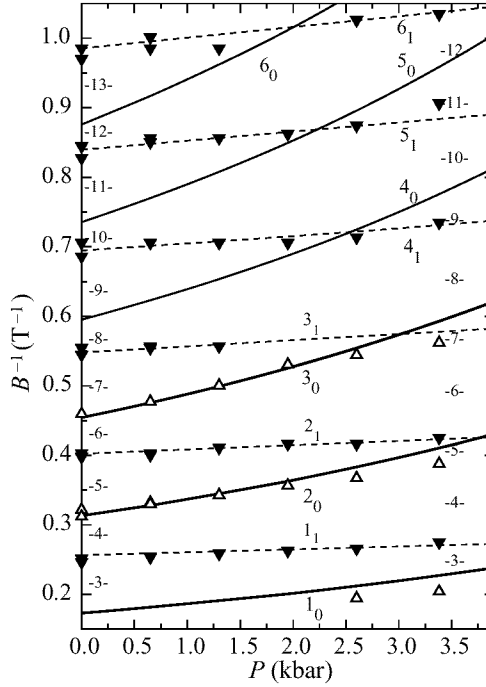


Fig 3. B^{-1} -positions of the SdH-maxima versus uniaxial (110) compression. The curves are calculated from the frequencies stated at Fig. 2 and the belonging phase factors, full: $B^{-1} = (n_0 + 1/2 - 0.263)/S_0$, dotted: $B^{-1} = (n_1 + 1/2 + 0.263)/S_1$. Filling factors at $P = 0$ and 3.38 kbar are shown as $-\nu$; they are calculated from the Hall densities.

frequency. In the transition region from 0.4 to 0.5 T^{-1} the oscillation pattern shifts to a higher frequency in the high-field range. In our previous analysis we found that the frequency ratio was close to 2, and was only modestly influenced by the uniaxial compression [5]. However, a strange feature was observed: The minima in the range of low fields are located at field values corresponding to *odd* filling factors, and these change to *even* at the maximal value of the uniaxial compression.

Now, having another look at the oscillation patterns, we note that the maxima moves differently under the application of the uniaxial compression: The maxima which at 0 kbar are located at 0.3 and 0.4 T^{-1} move closer to each other, while those at 0.25 and 0.3 T^{-1} move apart. With this observation as a guideline we then analysed the oscillations, assuming that they arise from two bands, each of which having a characteristic pressure dependence. The result is displayed in Fig. 2, where we show the Shubnikov-de Haas frequencies of the two bands as function of the uniaxial compression. As would be expected, the two frequencies are rather close to each other; but the dependence on pressure reveals a distinct difference. The carrier density calculated from the sum of the frequencies corresponds well to the Hall density.

In Fig. 3 we show the B^{-1} — positions of the maxima versus pressure, n_0 and n_1 indicating the Landau level numbers of the two bands. Positions of minima calculated from the Hall densities at zero pressure and at maximum pressure are shown by symbols $-\nu$, where ν indicates the filling factor. Comparing this figure with Fig. 1 we observe

the following features: Starting at the largest fields, the SdH-minimum corresponding to $\nu = 3$ falls between the maxima $n_0 = 1$ and $n_1 = 1$. The next minimum, $\nu = 4$, falls between $n_1 = 1$ and $n_0 = 2$, and like the $\nu = 3$ minimum it is clearly displayed at all pressures. The $\nu = 5$ falls between $n_0 = 2$ and $n_1 = 2$. On increasing pressure, these two maxima approach each other and the minimum becomes squeezed between them. The $\nu = 6$ minimum falls between the closely spaced $n_1 = 2$ and $n_0 = 3$ maxima at $P = 0$; however, as P increases, these two maxima go apart, and so the minimum becomes more pronounced on increasing P . Contrary to this, the $\nu = 7$ minimum at $P = 0$ falls between the maxima $n_0 = 3$ and $n_1 = 3$ and does show up; however, as P increases this minimum is squeezed between the two maxima, as was the case for $\nu = 5$. In this way we have reached an understanding of the *odd-even* problem mentioned above.

In conclusion, through investigation of SdH effect in symmetrically grown quantum wells under uniaxial compression we have demonstrated that the ground heavy hole state, instead of being doubly degenerate, consists of two slightly splitted bands.

Acknowledgements

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